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National Aerospace Laboratory NLR

NLR-TP-2002-689

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This report is based on a presentation held at the Advanced Workshop on Air Traffic Management (ATM 2002), Capri, Italy, 22-26 September 2002.

Customer:	National Aerospace Laboratory NLR
Working Plan number:	L.1.A.2
Owner:	National Aerospace Laboratory NLR
Division:	Air Transport
Distribution:	Unlimited
Classification title:	Unclassified
	December 2002

Contents

(17 pages in total)

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Paper for advanced workshop
"ATM architectures and CNS technologies needed to cope with
air traffic capacity problem, and related evaluation tools"

Abstract

The paper shows the results of a collision risk assessment based evaluation of safe spacing and safe separation criteria for a particular airborne separation assurance based operational concept. Assessed are both the model based risk and the bias and uncertainty that is caused by differences between the model and reality. It is also shown how accident risk results provide effective feedback to the concept design process.

1 Introduction

By exploiting advances in flight deck technologies, such as Airborne Dependent Surveillance - Broadcast (ADS-B), and air-to-air data link, airborne separation assurance is seen as a promising option for the future Air Traffic Management (ATM) concept, to provide an increase in capacity and flight efficiency while maintaining flight safety. The clear advantage of airborne separation assurance is that it may eliminate the sector capacity/safety bottleneck of ground based separation assurance, leading to an expected great improvement of the capacity of current sectors. The general expectation is that sector capacity may improve significantly even if spacing and separation criteria would stay the same. At the same time, it is also generally accepted that also a particular airborne separation assurance based operational concept will have its own capacity/safety limitations. Hence, many studies or expectations are based on particular hypotheses about the achievable spacing or separation criteria. Optimistic views are that they could be much smaller than radar separation; other views are much more reserved and warn that minimum separation distances might be much larger. In any case, there is a clear knowledge gap on this subject, and no provisions in ICAO. Thus, it is important to assess the relationships of spacing between flight plans, separation between airpaths, and safety, as they directly affect the effectiveness of an airborne separation assurance application.

Since collisions occur very infrequently, even for current ATM procedures there is not sufficient statistical data to verify evaluated collision risk results in a direct way against operational data. For new operations, such as autonomous aircraft operations, there even is far less operational data available. Therefore, one has to rely on model-based risk assessment to gain insight into this complex matter. It can help to learn where unsafety comes from, how it is influenced, which factors have the highest impact, and what contribution is coming from separation distances.

In this paper, we present the results of a model-based accident risk assessment for a hypothetical situation in which aircraft equipped for free flight are assumed to maintain separation without direct involvement of Air Traffic Control (ATC). For the accident risk assessment, we consider the flow of traffic between two major airports only, say A and B, and assume that the aircraft fly on direct routes between these two airports. Moreover, we consider the aircraft to fly at one flight level, and that flows of traffic going from A to B are naturally separated from flows going from B to A by the following procedure: aircraft will always stay a few miles to the right hand side of the direct route centreline. In fact, this means that the flows on this direct route are organised along two opposite direction lanes, see Figure 1.

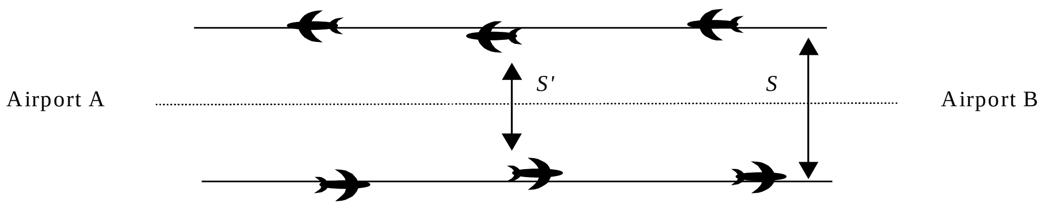

Figure 1: *Top view of two opposite direction parallel lanes at the same flight level. S denotes spacing, S' denotes lateral separation minimum.*

In Figure 1, S' denotes separation minimum and S denotes lateral spacing between the parallel opposite direction lanes. If the spacing S is taken to be equal to or smaller than the separation minimum S', it would be quite likely that two aircraft on two opposite direction lanes often need to manoeuvre in order not to lose minimum separation. Hence, an effective safe spacing level for S should at least be larger than a safe separation minimum S'. Both for S and S', it is important to further learn understanding what criteria should apply. Obviously, in a full free flight situation, there are many other encounter types that have to be studied (crossing routes, cross flight level, join same flight level, etc.). The idea is to understand the relation between accident risk and spacing for one encounter type first, before proceeding to study other encounter types.

The objective of this paper is to estimate safe values for *S* and *S'*, for a stream of aircraft that are all equipped according to the free flight operational concept outlined in Section 2. The safe spacing evaluation of opposite traffic streams within this operational concept is done using the accident risk assessment methodology of Blom *et al* (1998), which now includes a bias and uncertainty assessment stage (Everdij & Blom, 2002). The accident risk assessment methodology consists of an organised sequence of well-defined stages:

1. Identify the operation to be assessed and identify all relevant hazards.
2. Instantiate a mathematical model for the operation to be assessed.
3. Perform an accident risk assessment for this mathematical model of the operation.
4. Assess risk bias and uncertainty due to differences between the mathematical model and the real operation considered.
5. Compare the assessed accident risk levels with applicable risk criteria and evaluate the impact of separation criteria.
6. Assess the safety and spacing critical elements of the operation considered.

Of the application considered in this paper, stages 1, 2 and 3 have been executed in (Daams *et al*, 1999); stages 4, 5 and 6 have been executed in (Everdij *et al*, 2002). The main results of all stages will be presented in this paper. Section 2 presents the results of stage 1, Section 3 presents the results of stages 2 and 3, Section 4 presents the results of stages 4 and 5, Section 5 presents the results of stage 6.

2 The operational concept considered

The free flight equipment of the aircraft considered is based on an extension of an Initial Free Flight (IFF) operational concept developed by Hoekstra *et al* (1997). Based on the IFF accident risk assessment results (Daams *et al*, 1998), operational concept extensions have been developed, leading to the Extended Free Flight (XFF) operational concept. The main characteristics of XFF are as follows:

- Aircraft are equipped with ADS-B, and use this to inform other aircraft about both their position/speed and their intent (flight plan).
- Aircraft have medium term conflict detection and resolution (CD&R) automation support that detects conflicts between flight plans and proposes a flight plan resolution.

- Aircraft have Flight Plan Conformance Monitoring (FPCM) that detects severe deviations by both the own and the other aircraft from their respective flight plans and proposes a flight plan adjustment to increase separation.
- Aircraft have short term CD&R automation support that detects conflicts and gives resolution advisories which the pilots can confirm and then automatically fly.

Some additional explanation is given below.

2.1 Airspace organisation

The free flight airspace is not covered by radar and is without any ATC separation support. Aircraft are expected to fly direct routes between entry and exit points; however, the analysis of this operational concept is limited to one of these direct routes, with two parallel lanes with aircraft flying in opposite directions at the same flight level, see Figure 1. The number of aircraft that enters each lane per hour is assumed to be $N_{flow} = 3.6$. It is assumed that nominally, the aircraft flight plans are conform the parallel lanes and that the pilots should leave the sector at the exit point of their lane.

2.2 ADS-B

ADS-B is used to inform other aircraft of aircraft state (position and speed vector) and intent (flight plan) information. In flight, each aircraft broadcasts at an update rate of one per second nominally:

- the medium term flight plans (available in the FMS),
- the own state estimates (available from its navigation system).

Hence, the following information is available on board of each aircraft:

- The flight plan of the own aircraft.
- The estimated state of the own aircraft.
- The medium term flight plans of the surrounding aircraft (say, within 60 Nm radius).
- The state estimate information from the surrounding aircraft.

2.3 Medium term CD&R

Conflict Probing (CP) checks whether the flight plans of the own aircraft and the surrounding aircraft (which are available through ADS-B) are in conflict (i.e., distance smaller than S', see Figure 1) in medium term, and proposes a flight plan resolution. This is done on board of each aircraft, by testing whether a conflict between flight plans occurs within medium term (i.e. the next 5 minutes). If a conflict between flight plans is detected, the pilots-not-flying of the aircraft involved are both alerted through their displays upon which they both have the responsibility to adjust their flight plans by confirming the proposed resolution to increase separation (minimally S between the flight plans, where S equals the distance between the parallel lanes). Normally, only one aircraft adjusts his flight plan in response to the alert. The reason for this is that it takes some time before proper action is taken: if one aircraft adjusts his flight plan such that there is no conflict, there is no reason for the other aircraft to adjust his flight plan.

2.4 FPCM

The FPCM monitors whether the aircraft evolutions of both the own and the surrounding aircraft conform to their flight plans. This is done on board of each aircraft, by comparison of the aircraft filtered state and the flight plan for each aircraft. If the deviations between the aircraft filtered state and the flight plan are severe, i.e. pass a given threshold (taken about 1.5 Nm, which corresponds to the 98.5% boundary of ANP1), then the pilots-not-flying are alerted through their display. Also, a flight plan resolution is automatically proposed.

- If the FPCM alert concerns a severe deviation of some nearby aircraft from its flight plan, the pilot-not-flying has the task to adjust the flight plan of his own aircraft by confirming the proposed resolution to increase separation (minimally 10 Nm between the flight plans) with the deviating aircraft.
- If the FPCM alert concerns a severe deviation from the aircraft's own flight plan, the pilot-not-flying has the responsibility to advice the surrounding aircraft through R/T to increase the minimal separation between flight plans to minimally 10 Nm and to ask the pilot-flying to return to flight plan. Furthermore, the pilot-not-flying tries to solve the problem that caused the severe deviation. If necessary, the pilot-not-flying of another aircraft will adjust his flight plan to ensure this separation.

Adjustments in flight plan to ensure sufficient separation by deviating aircraft are assumed to consist of an immediate turn to the left or to the right, which heading is flown until the original heading can be resumed without compromising the desired separation between flight plans. If the point of closest approach is passed, each aircraft returns to its original flight plan. For the same reason as with medium term CD&R: normally, only 1 aircraft will adjust his flight plan.

2.5 Short term CD&R

The pilots of both conflicting aircraft are warned automatically if a separation conflict (i.e., distance smaller than S', see Figure 1) is expected to occur within 2 minutes on the basis of the neighbouring aircraft's estimated position and velocity vectors (which are available through ADS-B) and the predicted position and velocity (using linear prediction). After detection, a conflict resolution is proposed automatically for each aircraft using the Voltage Potential algorithm which proposes adjustments in the horizontal velocities (with no priority rules). After some time-delay (incurred by human response time) the pilot-flying will confirm the proposed conflict resolution. Then the resolution is carried out automatically and is continuously updated (every 10 seconds) effectively according the state estimate update without further pilot acknowledgements. Hence, normally, both aircraft will perform conflict resolution.

2.6 Priority rules in reacting to alerts

The following rules determine the priority of reacting to alerts:

- Short term conflict detection and resolution is handled with priority over CP or FPCM alerts. The underlying reason is that in case of a short term conflict, immediate action is required, whereas CP and FPCM alerts require action at planning level.
- If both CP and FPCM issue an alert, the FPCM alert is handled with priority. The underlying reason is that the aircraft that causes the FPCM alert cannot be expected to take effective action to ensure separation, since the pilots on board are probably preoccupied with repairing the problem that caused the alert. This is in contrast to the case of a CP alert, where it is reasonable to assume that the other aircraft will also taken action.
- An FPCM alert concerning the own aircraft has priority over FPCM alerts concerning other aircraft. This is due to the observation that in case that the own aircraft cannot adhere to the flight plan very well, adjustments of the flight plan to avoid some other aircraft are not expected to be very effective. Therefore, priority lies with warning the other aircraft (in case they have not detected the deviation themselves yet) and solving the problem on board.

2.7 XFF-specific human responsibilities

The general responsibilities of the pilot-flying and the pilot-not-flying are to carry out the mission of the aircraft in a safe and efficient manner. The XFF-specific responsibility of the pilot-flying is the correct execution of the flight plan. The responsibility of the pilot-not-flying is to respond to any CD&R automation messages by looking at the CD&R traffic screen and taking appropriate actions. It is assumed that the pilots do not take over each other's role. ATC is only involved when an aircraft leaves or enters the free flight airspace considered.

2.8 Radio communication

For emergency situations (e.g. to warn other aircraft in case of severe deviations from flight plan due to aircraft system problems), the pilots-not-flying have radio only to communicate with each other.

2.9 Navigation

Aircraft navigation performance is assumed to be RNP1, which means that an aircraft stays within ± 1 Nm of its flight plan for 95% of the time. Ground navigation support is VOR/DME.

3 Model based risk assessment

The accident risk assessment performed for the XFF operational concept, restricted to the situation of the two opposite direction parallel lanes, was based on dedicated Monte Carlo simulations of a mathematical model. This mathematical model is instantiated in several steps.

The first step involves the identification of as many hazards that may occur during the XFF operation as possible. These hazards have been identified using dedicated brainstorm sessions with experts from various expertise. For XFF, about 230 hazards have been identified; the list is provided in (Everdij *et al*, 2002).

In the second step, the operational concept description and the list of hazards is investigated to identify the actors/entities of the XFF operation. These actors may be humans (pilot-flying; pilot-not-flying), technical systems (navigation support; ADS-B; cockpit display; FPCM, etc.), or even more abstract entities (e.g. pilot training; weather; aircraft mission; aircraft evolution). For XFF, the complete list is provided in (Daams *et al*, 1999).

In the third step, a mathematical model is developed for the XFF operation. For this, the Dynamically Coloured Petri Net formalism (Everdij & Blom, 2000) is used. A Petri net is a graph of places (representing possible conditions or modes), transitions (which model switches between these modes), and arrows (which connect the places with the transitions). Tokens residing in the places denote which modes are current. If all places by which a transition is connected through an incoming arrow (i.e. its input places) are current, then the transition is enabled, and it removes the tokens from its input places, and produces tokens for its output places, thus modelling a mode switch. A Dynamically Coloured Petri Net is an extension in which stochastic differential equations are coupled to places, and a token in a place has a colour, assuming multi-dimensional values, which is the solution of the place-specific stochastic differential equation and which receives its initial value from the preceding transition switching. Transition switching itself may depend on the evolving colour values of the input tokens of the transition.

First, local Petri nets are instantiated for each actor/entity. Next, the local Petri nets are coupled with additional arrows, places and/or transitions, modelling the interactions and dependencies between the actors/entities. The whole DCPN model building process usually takes several iterations, in which both the local Petri nets and the interactions are updated. After the final iteration, the DCPN forms a mathematical model of the evolution of the states (e.g. position and velocity) of flows of aircraft as a function of time, influenced by the behaviour (both nominal and non-nominal: hazards) of all actors/entities existing in the XFF operation. For the XFF example considered in this paper the DCPN instantiation is specified in (Daams *et al*, 1999).

The fourth step makes use of an expression for collision risk (Bakker & Blom, 1993) which includes as baseline the ICAO-adopted model of Reich (1964) for risk of collisions between aircraft. The expression writes collision risk $\Re_{[0,T]}$ within some time interval $[0,T]$, as a function of the incrossing rate $\varphi^{ij}(t)$ of the relative position of two aircraft i and j into some collision area:

$$\Re_{[0,T]} = \sum_{i=1}^{n} \sum_{j>i}^{n} \int_{0}^{T} \varphi^{ij}(t)dt$$

This incrossing rate might be evaluated using Monte Carlo simulations of the DCPN instantiation. However, since collisions occur very infrequently, they are not counted very often, and direct Monte Carlo simulations may not produce significant results. For this reason, collision risk is decomposed into sums of risk contributions of specifically defined events in time, as in the following equation:

$$\Re_{[0,T]} = \sum_{i=1}^{n} \sum_{j>i}^{n} \sum_{\kappa} \int_{\tau^{ij}}^{T} \varphi^{ij}(t \mid \kappa_{\tau^{ij}} = \kappa)dt \cdot \Pr\{\kappa_{\tau^{ij}} = \kappa\},$$

where $\varphi^{ij}(t \mid \kappa_{\tau^{ij}} = \kappa)$ is the incrossing rate, conditional on event $\kappa_{\tau^{ij}}$ of type κ at moment τ^{ij}, and $\Pr\{\kappa_{\tau^{ij}} = \kappa\}$ is the probability that event type κ occurs prior to any of the other defined events. If the events are chosen well, each of the individual factors in this expression can be evaluated through dedicated Monte Carlo simulations.

After performing these dedicated Monte Carlo simulations on the DCPN instantiation for the XFF example, we assessed the risk contributions in the equation above and combined these to obtain accident risk as a function of the spacing parameter *S* (connected curve in Figure 2), which is from (Daams *et al*, 1999). The horizontal axis shows the spacing *S*, the vertical axis shows the number of aircraft accidents per aircraft flight hour that can be expected for this spacing.

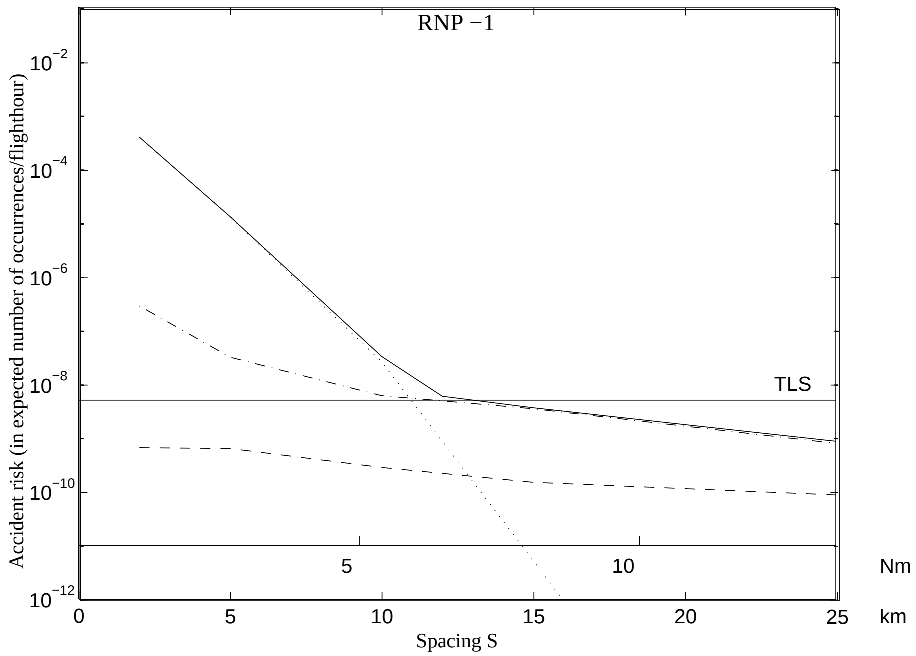

Figure 2: *Risk-spacing curve for XFF-DCPN model (—), which is a sum of three curves; '...' denotes contribution to risk from encountering aircraft that are both in Nominal mode; '-·-·' denotes contribution to risk from encountering aircraft of which one is in Nominal mode and one is in Non-nominal mode; '---' denotes contribution to risk from encountering aircraft that are both in Non-nominal mode. The horizontal line is a currently applicable Target Level of Safety (ICAO, 1998)*

The risk-spacing curve for the XFF-DCPN model intersects the TLS at S = 7 Nm, which would indicate that based on the DCPN model instantiated for the XFF-equipped operational concept, a distance of S = 7 Nm between the parallel lanes is safe.

In Figure 2, the risk-spacing curve is decomposed into a sum of three curves (each curve is based on clusters of event types):

- '...' denotes contribution to risk from encountering aircraft that are both in nominal mode;
- '-·-·' denotes contribution to risk from encountering aircraft of which one is in nominal mode and one is in non-nominal mode;
- '---' denotes contribution to risk from encountering aircraft that are both in non-nominal mode

It appears that for S smaller than 7 Nm, the contribution from encountering aircraft that are both in nominal mode (curve '...') is dominant. For S greater than 7 Nm, the contribution from encountering aircraft of which one is in nominal mode and the other is in non-nominal mode (curve '-··-··') is dominant. These two contributing factors lead to two curves with different slope. Their sum creates a curve which has a bend.

Further analysis yields that if S' (separation minimum) and S (spacing) are jointly optimised, the following results are obtained: safe $S' = 5$ Nm, safe $S = 7$ Nm. Moreover, it becomes clear that for the XFF-DCPN model, accident risk is more sensitive to spacing S than to separation minimum S'.

4 Bias and uncertainty assessment

So far, we took a formal modelling approach towards the accident risk assessment. This means that accident risk is assessed for the instantiated model of the XFF example. One thing is sure, for operations as complex as the XFF example considered, a model will always differ from reality, and thus model validation cannot be a matter of showing that the model equals reality. The validation problem rather is how to verify that the model 'matches' reality sufficiently well, with respect to the intended use of the model. An absolute 'match' is neither feasible nor necessary. Thus, validation addresses the questions:

- how much differs the instantiated model from reality, and
- how large is the effect of these deviations on the outcomes of the assessment?

Hence, it is necessary to bring the model assumptions made to the foreground and subsequently perform an analysis of their effects on accident risk.

Four types of model assumptions are identified in (Everdij & Blom, 2002) that influence these effects:

I. Numerical approximation assumptions;
II. Parameter values;
III. Model structure assumptions;
IV. Assumptions due to Non-coverage of hazards.

The effect of each model assumption on accident risk can be of two kinds:

- Bias; due to the adoption of the formal model assumption, the DCPN model-based accident risk is systematically higher or lower than expected for the real operation.
- Uncertainty; there exists uncertainty in the DCPN model-based accident risk, for example due to uncertainty in the value of some parameter.

In (Everdij *et al*, 2002), the bias and uncertainty of each individual assumption has been assessed, and next all results have been combined to obtain a model bias compensation factor and 95% credibility interval for risk of the actual operation. For the XFF-DCPN model, this covered 122 assumptions:

- 7 assumptions due to numerical approximation have been identified and assessed by an expert of both the DCPN model and its numerical implementation.
- 70 assumptions due to selection of DCPN model parameter values have been identified by scanning the DCPN model description as documented in (Daams *et al*, 1999), and have been verified by an expert of the numerical implementation of the DCPN model. The bias and uncertainty of these values have been assessed by using statistical data, and by using input from operational experts. The risk sensitivity of these values has been assessed through expert knowledge of the DCPN model and software, and through (partial) accident risk evaluations of the DCPN model.
- 23 assumptions due to model structure of the DCPN model have been identified and assessed by stochastic experts of the DCPN model.
- 22 assumptions due to non-coverage of hazards have been identified and assessed as follows: Each of the hazards identified for XFF has been analysed by experts of the DCPN model on coverage by the DCPN model. If a hazard appeared not to be covered, an assumption was formulated to explain this. The resulting list of assumptions has been assessed by operational experts.

Since the assessments of these differences often are subjective, the outcome depends on the availability of capable experts of the model, the accident risk assessment and the operational concepts considered, on the exhaustiveness of the hazard identification, and on the availability of reliable statistical data.

The bias and uncertainty assessment results obtained for XFF are given in Figure 3. For comparison, the figure shows the DCPN model-based risk-spacing curve together with is decomposition as a sum of three curves (see Figure 2).

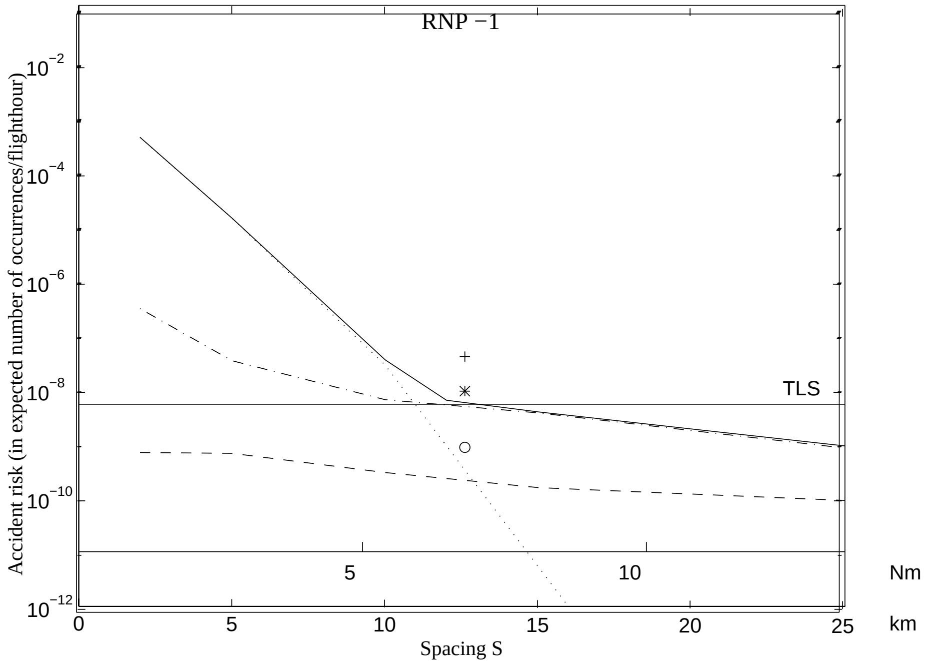

Figure 3: *The connected curve is the XFF-DCPN-based risk-spacing curve, decomposed as a sum of three contributions as in Figure 2. The * denotes DCPN model-based accident risk, corrected for the effects of the four types of model assumptions. The 95% credibility interval for XFF is given by o and +.*

Notice that the assessments of the assumptions apply to changes of the risk-spacing curve for the XFF-DCPN model at one value for *S*: at the point where the curve intersects the target level of safety. Also note that some of these assumptions will have an effect on the nominal × nominal curve, others will have an effect on the nominal × non-nominal curve, etc., or even on more than one curve. From this, it is easily seen that the assessments of these assumptions do not necessarily hold for all values of *S*. However, if we assume that they do hold for values of *S* nearby this intersection point, the expected risk-spacing curve for XFF intersects the TLS at *S* = 9.0 Nm. The assessed 95% credibility interval for XFF accident risk would then intersect the TLS at *S* = 5.4 Nm and at *S* = 14.4 Nm.

5 Feedback to airborne separation assurance concept development

The bias and uncertainty assessment showed that the main factors contributing to bias and uncertainty in the model assessed risk values are:

- Response times of the pilots to CD&R and FPCM messages when they are busy with other tasks.
- Aircraft that do not have a properly working ADS-B on board.
- Short term CD&R also proposing vertical escape manoeuvres.

These factors are potential candidates to be further studied and when better understood they may be incorporated in an improved DCPN model, and subsequently be incorporated in an update of the risk assessment. It is important to be aware that such DCPN model improvement is expected to yield new valuable insight in airborne separation assurance design.

Based on the risk assessment results obtained, it also is possible to identify for some operational aspects how they influence safe *S* values for the XFF operational concept:

- A lower flow of traffic between airports A and B in the model is expected to lead to a marginal improvement of the safe *S* value only. The reason is that although accident risk will go down, the quite steep slope of the nominal curve in Figure 3 will prevent the safe *S* value from going down significantly.
- A higher flow of traffic between airports A and B in the model is expected to lead to a significant increase of the safe *S* value. The reason is that accident risk will go up, and the quite shallow slope of the non-nominal curve in Figure 3 will lead to significant increase of the safe *S* value.
- Without the broadcast of intent information by all aircraft it is expected that the safe *S* value increases significantly. The reason is that when pilots are not able to make medium term flight plans that are conflict free then all conflicts have to be resolved on short term; this was studied in (Daams *et al*, 1998).
- Leaving out FPCM automation is expected to lead to a significant increase of the safe *S* value. The reason is that in such case the nominal × non-nominal curve is expected to shift to significantly higher risk values.
- Relaxing required navigation performance, e.g., from RNP1 to RNP5, is expected to lead to a significant increase of the safe *S* value. The reason is that the steep part of the curve in Figure 3 will get a much shallower slope.
- The accident risk appears to be significantly less sensitive to changes in the value of the separation minimum S’ than to changes in the spacing value S.

At all times, one should be aware that the above findings have been obtained within the context of the hypothetical XFF operational concept considered. Nevertheless the findings obtained give a lot of valuable and original insight both into key issues of airborne separation assurance design and in safe spacing and separation criteria assessment for advanced ATM.

6 Concluding remark

In this paper, a hypothetical airborne separation assurance operational concept has been evaluated on safe spacing and separation criteria. This is done by assessment of both the model based risk and the bias and uncertainty that is caused by differences between the model and reality. In particular, due to the decomposition of the total risk curve into different contributing terms, the results deliver valuable feedback to airborne separation assurance design. In fact, some of these feedback results have already been obtained in (Daams *et al*, 1999). However, it is due to the added bias and uncertainty assessment of (Everdij *et al*, 2002) that we reached a level of confidence necessary for publishing the results. We also believe there is room for valuable extensions in the bias and uncertainty assessment: bias and uncertainty assessment may be done for all values of *S* and for each of the risk contributing terms.

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